<u>Life and Death of Stars in our Universe</u>

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Stars live and die based on the balance they create between the (1) outward force of the energy released from their cores when their hydrogen atoms fuse into helium atoms and (2) the inward force of gravity of the hydrogen, helium, and the later stage heavier elements created in the core. Understanding this balance and what a star actually is, will also lead to an understanding of the life cycle of stars and the fascinating events and objects created at star death.

Due to the fact that hydrogen is the most abundant element in the Universe (it is also the lightest and simplest element, which is actually also the reason that it is the most abundant), stars can maintain this energy source for most of their lives. This process is called the main sequence phase because it is describing the prolonged adolescence or adulthood of a star. Many stars live almost 91% of their lives in this phase.
They fuse hydrogen atoms into helium atoms in their cores in, quite literally, a nuclear furnace. In fact, the simplest definition of a star is "a cloud of hydrogen in space which is dense enough that the hydrogen atoms begin to fuse into the next heaviest element, helium". As the fusion reaction is occurring, extremely high energy is released as an outward force; however, the star doesn't just explode small at once, because the inward pull of gravity on the outer layers of hydrogen balances out the outward force of the nuclear energy from the fusion reactions in the core. This balance persists from the moment of birth of a star until the hydrogen begins to run out, thrusting the star into its death phase, and is known as the main sequence of the star.

The length of time a star remains on the main sequence phase is based on its mass. You might think that a massive star, with more fuel, would last longer, but it is the complete opposite. The lifetime of a star depends on how much nuclear fuel it has and on how quickly it uses it up. Therefore, more massive stars use up their fuel more quickly than low mass stars.
The reason that these massive stars are such "spendthrifts" is that the rate of fusion depends very strongly on the core temperature of a star. You might ask what determines how hot the core gets, and the answer is the mass. To explain more thoroughly, the weight of the outer layers determines how high the pressure is in the core: higher mass requires higher pressure. This high pressure is produced by high temperature. Knowing all of this, we can say that the higher the temperature in the core of stars, the faster the star converts its central hydrogen. This explains why the massive main-sequence stars are also the most luminous.
The next thing that happens in a star's demise is when the hydrogen in the star's core is all used up. During this, the core only contains helium as well as whatever small percentage of heavier elements the star had to begin with. The helium in the core can be described as a pile of ash that is left over from the nuclear 'burning' of hydrogen from the main sequence stage. At this stage, the star's luminosity decreases. Now, with just helium at the core the gravitational pressure will push on the core until it begins to collapse. As the core collapses, the temperature increases as there is more pressure build up. You might ask if helium fuses into anything, and the answer is yes. Helium fuses into the next, and then the next heavier elements in

order...Lithium, Beryllium, Neon, Carbon, Oxygen, etc. However, ever higher temperatures and pressures are required to reach these stages (100 million Kelvin and more, to be exact).

As this core continues to collapse, it reaches higher and higher temperatures. There is also a shell of hydrogen that exists around the core that did not have a chance to burn in the core in the beginning. As this layer hydrogen starts to burn with the collapsing core, the outer layers of the star begin to expand. We know that when things start to expand, they cool. At this stage, the star is burning shell hydrogen rather than core hydrogen. This stage is called the Red Giant branch.

Now, as the hydrogen keeps burning, the helium ignites to produce the next heavier elements in the core. With this added pressure, the outer layer of the star expands even more. However, the temperature heats in the core and cools as it expands, so balances out to its initial temperature. This is called the horizontal branch when the star burns not only shell hydrogen, but core helium as well.

What happens next is that the shell hydrogen begins to run out, and the core helium begins to run out. Now, the core begins to collapse once more. This carbon and oxygen core looks to burn. Carbon burns to neon and magnesium. It also turns out that there are more layers of hydrogen and helium that did not burn in the first three stages. When these shells burn, the energy release pushes on the outer layers of the star even more. This stage is called AGB, when the helium and hydrogen layers burn to cool and expand the star even more.

To put it simply, the star has reached the point of disaster. The star has grown almost 1,000 times its original size. When our sun reaches this point, it will have enveloped the orbit of Mercury, Venus, and even Earth. You might ask if the star can burn carbon and oxygen in the core. Well for smaller stars, that might be a step too far. It turns out that any star that is less than 8 times the mass of the Sun (or 8 solar masses) will never burn carbon and oxygen. Stars beyond that size will burn beyond carbon and oxygen and will end up going supernovae which have the potential to become black holes and will be discussed later.

What ends up happening with low mass stars, is that the carbon and oxygen in the core that cannot be burned begins to collide with other carbon and oxygen shells. In turn, the electrons within the carbon and oxygen start to collide. This step is called Electron Degeneracy Pressure, or EDP. What ends up happening is that the electrons begin to repel each other which expands the outer layers of the star even more. These outer layers begin to diffuse into a massive cloud of material which is called a planetary nebula. The name originated from the fact that when astronomers looked at them through their telescopes, they resembled planets. When in fact they have nothing to do with planets. There are tens of thousands of these planetary nebulae in our Universe, although many are hidden from view because their light is absorbed by interstellar dust. As this cloud of material begins to expand, a carbon and oxygen core is left behind. You might wonder what is holding it together and it is not fusion, but by electron degeneracy pressure as mentioned earlier.

This pile of left-over material is known as a white dwarf as it is white hot from the massive pressure as well as extremely dim. The white swarf will be the size of approximately 1.4 solar masses. This is called the Sandra Chakar limit, named after the scientists who was able to calculate this and won the Nobel Prize for this discovery. As time goes on, this white-hot white dwarf begins to cool. This object is so dense that one teaspoon of the material weighs ten tons! Now we end up with this floating condensed material that centers around expanding clouds of dust in the form of a planetary nebula.

As promised, I will next discuss what happens when a star greater than 8 solar masses begins to die. In fact, stars that are this large are relatively rare in our Universe as they die so quickly. Well, there are stars this massive in the universe and they have the ability to bypass Electron degeneracy pressure. They keep burning through the elements until they reach temperatures more than billions of degrees Kelvin. They burn larger and larger elements, until the reach Iron (Fe) at 2.7 billion kelvins. Similarly, to how EDP is what causes smaller stars' demise, iron is a major issue for high mass stars. You might be wondering why larger elements cannot be created, and they can. However, you must add energy to iron in order to do this. You cannot 'squeeze' anymore energy out of iron. With more burning and burning, the core eventually reaches the temperature of 5.5 billion K. The iron that is sitting in the core is actually disintegrated and destroyed from the energy of the heat. This is known as Photodisintegration. In this event, the iron is ripped apart to the extent where we are just left with protons, neutrons, and electrons. Almost immediately, the protons and electrons combine to form neutrons which sends out bursts of neutrinos. Ultimately, the core becomes a big ball of neutrinos which don't want to combine or go any closer together. These neutrons are packed so tightly and Neutron Degeneracy Pressure (NDP) is created. Now, materials begin to try to collide with the core of neutrons, but the core is so dense that they begin to reflect off. This is called Core bounce. The star begins to rip itself apart, material flying everywhere. This destruction is what's known as a supernova. This is an extremely energetic event and this star becomes as bright as billions of stars. So energetic in fact that is second only to the Big Bang. Through this event, all the elements in the Universe are created which lead to the formation of life, planets, and yet more stars. The only survivor of this catastrophic event is the ball of neutrons held together by NDP. It is only 8-20 kilometers across and is known as a neutron star. It is extremely dense that one teaspoon weighs approximately 1,000,000,000 tons! Almost 100 million times that of an Electron 'star.' They have so much gravity that the escape velocity needed (the speed you need in order to escape the gravitation pull) is half the speed of light. Although this might sound like one of the most extreme events, it is not the end. In fact, stars that are amazingly large collapse further into singularities. A singularity can be described as a singular point that the escape velocity is greater than the speed of light! This extremely large remnant of an enormous supernova is called a black hole. The gravitational pull is so great, that nothing can escape. However, contrast to popular belief, nothing is sucked in. You can orbit a black hole, but if you are too close you will be dragged in as nothing can escape the gravitational pull. This summarizes the most extreme end fate of a catastrophically large supernova coming from an even larger star.

You might want to know what might happen if you were dragged into a black hole. Luckily, scientists have modeled what might happen if an astronaut, for example, might fall in. At first, the astronaut might fall away from the spaceship, moving faster and faster as if he was approaching a massive star. As he nears the event horizon (the point that nothing can return or escape), things start to change. The strong gravitational field will make the astronaut's time run more slowly. To explain, if, as he approaches the event horizon, he sends out a signal once per seconds according to his clock, we will see the spacing between his signals grow longer and longer until it becomes infinitely long. He will soon appear to be frozen in place from an outside observer. However, to himself he has been moving at the same rate the whole time. Unfortunately for the astronaut, once absorbed by the event horizon there is no turning back. The astronaut will soon be stretched and squeezed to a point called spaghettification. The point at which the astronaut perished is based off the mass of the black hole. With black holes with the mass of a few solar masses, the astronaut will be spaghettified before he even reaches the vent horizon. With black holes that are larger, he might be completely absorbed before the process even begins!

You might want to know how we can track black holes if they are invisible to our eye. We can simply search for star whose motion shows that it is member of a binary star system (a system in which two stars orbit each other). If both stars are visible there is no black hole, however if there is only one star visible in the system, there is a possibility. However, being invisible to a telescope is not enough because a relatively faint star could be hard to make out next to the glare of a larger, brighter companion. So, astronomers look to see if matter falls toward something and accelerates to high speeds. Near the event horizon of black holes, objects will accelerate to speeds approaching the speed of light. Since the matter might be rotating, the matter will spiral around the black hole as it is falling. This creates gas whirls which are called accretion disks. The internal friction within the disks is heated to X-ray-emitting temperatures. If astronomers look for these X-rays, they might confirm the presence of stellar black holes. However, neutron stars also produce X-rays so astronomers must study the properties of these emissions very carefully to determine what they are.

Some might know that there are massive black holes in the center of galaxies. However, it is known that these central black holes differ greatly from the stellar black holes dispersed throughout our Universe. The central black holes have a much better opportunity to pull in ‘unsuspecting victims’ in the form of asteroids, gas, dust, stars, and even other black holes. This is because in the centers of galaxies, the stars and raw materials are very crowded together. As a result, these central black holes can grow millions of times the mass of our Sun. Calculations have proven that the black hole in the center of our galaxy is approximately four million times the mass of the Sun which is extremely large!

Through the description of the death of low and high mass stars, to the creation of white dwarfs, neutron stars, and massive stellar black holes, our Universe is a catastrophic place. In an environment where more and more elements are formed every day, there are trillions of opportunities for life to thrive.